MONTHLY
WEATHER
REVIEW

VOLUME 93, NUMBER 5

MAY 1965

# THE PREDICTION OF SURGES IN THE SOUTHERN BASIN OF LAKE MICHIGAN

## Part I.[1] The Dynamical Basis for Prediction

GEORGE W. PLATZMAN

The University of Chicago, Chicago, Ill.[2]

ABSTRACT

A summary of numerical computations is presented, in a form designed to aid in operational prediction of surges in the Southern Basin of Lake Michigan. The computations are based upon a dynamical model in which the surge is generated by pressure gradient and wind stress in a squall line which moves across the Basin with constant speed and direction. For each of 25 combinations of squall-line propagation speed and direction, the arrival time of the surge is determined, and the amplitude estimated, at various locations along the shore. At some locations there are a well-defined peak of surge amplitude and corresponding critical values of squall-line propagation speed and direction, associated with resonant coupling between the squall line and Lagrangian body waves. Energy computations indicate the presence of another resonant peak associated with Stokesian edge waves.

## 1. INTRODUCTION

This is the first of three papers that appear in this issue of the *Monthly Weather Review* under the general title "The Prediction of Surges in the Southern Basin of Lake Michigan." These papers are concerned with an atmosphere-lake interaction problem which first attracted attention as a result of the notable surge of water level that occurred along the Chicago lakefront on June 26, 1954. Their aim is to describe theoretical and empirical knowledge of the characteristics of such surges, acquired at intervals during the ten years since 1954.

The first paper gives a summary of theoretical results obtained by means of numerical model calculations. Part II (by S. M. Irish [5]) is a case study of the surge of August 3, 1960, with emphasis on analysis of the associated atmospheric mesoscale disturbance. Part III (by L. A. Hughes [4]) describes an operational prediction scheme which incorporates some aspects of the theoretical results, as well as experience gained in connection with the surge of August 3, 1960. This scheme has been in use for several years at the Weather Bureau's Chicago Forecast Center.

The surges of water level studied in these investigations are caused by intense squall lines that move rapidly across the Southern Basin of Lake Michigan in a direction generally toward the southeastern quadrant. The accompanying pressure gradient and wind stress acting on the lake surface can produce an organized mid-lake disturbance which resembles a solitary wave. Upon arrival at the lake shore, this wave can create large changes of water level through the operation of shoaling effects.

A few references to the literature on this subject are given in [7]. For an extensive bibliography on the general problem of meteorologically-induced water-level changes, see [8].

## 2. DYNAMICAL-NUMERICAL MODEL

The numerical results described in this paper were obtained in conjunction with an earlier study [7] of the surge of June 26, 1954. That study employed an idealized model of the distribution of pressure and wind in the

[1] Part II (by S. M. Irish) and Part III (by L. A. Hughes) appear elsewhere in this issue of the *Monthly Weather Review*.

[2] This investigation was supported through funds provided by the U.S. Weather Bureau (Contract CWB-9984) and by the National Science Foundation (Grant NSF-GP-471).

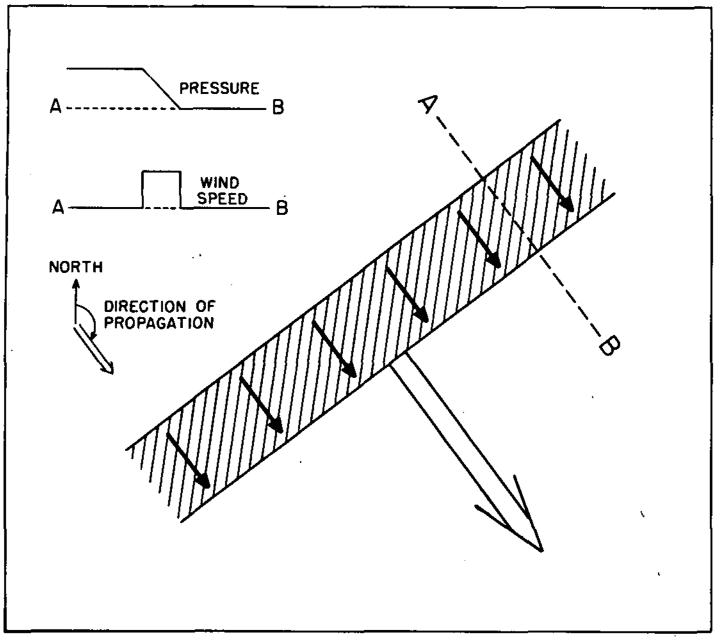


FIGURE 1.—Idealized squall-line configuration used in numerical model of surge generation. Insets show pressure and wind-speed distributions in a section perpendicular to the squall line, and definition of angle used to specify direction of propagation vector.

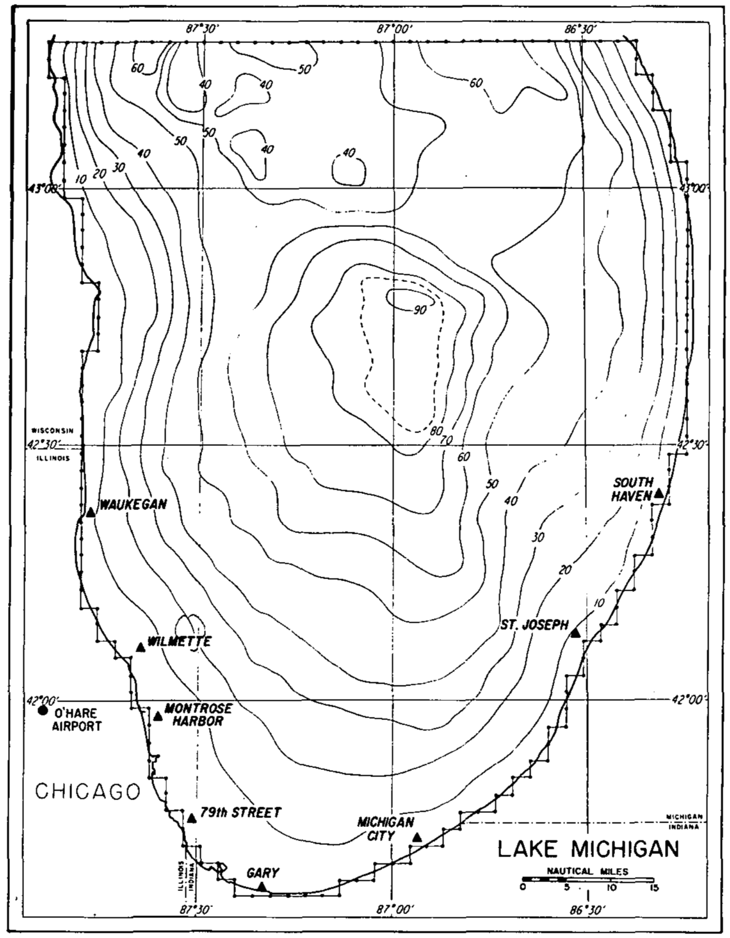


FIGURE 2.—The Southern Basin of Lake Michigan. Depth contours are marked in fathoms (1 fathom=6 ft.) Small, black triangles show locations of grid-point stations to which reference is made in figures 4 and 5.

squall line, illustrated in figure 1. The shaded band in this figure is the rectilinear zone in which the squall-line pressure gradient and wind are assumed to be localized; this zone moves with constant speed and direction. Ahead of the band and behind it the atmospheric pressure is uniform (zero pressure gradient) and the wind calm. Within the band, atmospheric pressure increases uniformly from front to rear (with no transverse gradient), and the wind is uniform both in speed and direction.

In the numerical model the idealized squall line is caused to move across the Southern Basin of Lake Michigan, with prescribed speed and direction. The resulting disturbance of lake level is computed on a grid with mesh interval 2 n. mi., by means of an initial-value formulation of the dynamical problem, with time step equal to 1 min. The dynamical equations used are those appropriate for a homogeneous, incompressible fluid; frictional and Coriolis forces are ignored, and the equations are linearized. (For further details, see [7].)

The region of integration is shown in figure 2. It consists of the entire Southern Basin, and is closed on the north by an artificial boundary that extends straight across the lake at latitude 43°17′ N. The shore of the basin is approximated by a "zig-zag" line, the corners of which are located at grid points (see fig. 2). The entire boundary (including the artificial segment on the north) is regarded as a totally-reflecting, rigid barrier; thus, the normal velocity component is assumed to be zero everywhere on this boundary.

In each of the numerical computations the initial conditions are such that the lake is at rest and the leading edge of the squall line is located at the upper left (northwestern) corner of the grid (see fig. 2). The squall line then begins to move across the basin with prescribed speed, direction, and intensity. The numerical values selected for these parameters are given in the next section. By examining the time history of the resulting lake-level variation, it is a simple matter to determine the amplitude and arrival time of the surge at specific locations on the shoreline. These results are given after the next section.

## 3. SPECIFICATION OF SQUALL-LINE PARAMETERS

A separate surge computation was made for each of the 25 combinations of squall-line propagation direction and speed that arise from the following five directions and five speeds:

*direction:* 95, 115, 135, 155, 175 degrees

*speed:* 42, 48, 54, 60, 66 knots.

In figure 1 is indicated the definition of the angle used to describe the propagation direction. The propagation direction 95° (for example) is 5° south of west-to-east and corresponds to a squall line oriented 5° clockwise from north-south, whereas 175° is 5° east of north-to-south and corresponds to a squall line oriented 5° counterclockwise from west-east. The five directions listed above span the southeast quadrant of propagation directions, which is the quadrant of most frequent occurrence in the upper Midwest.

The five speeds were selected with the aim of bracketing the resonant speed believed to be between 50 and 60 kt. and with a view to the squall-line speed of 66 m.p.h. (57 kt.) reported by Ewing, Press, and Donn [2] and 56 kt. by Harris [3], for June 26, 1954. Since the modal propagation speed of squall lines in the Midwest probably falls below the range selected for computation, it would be useful to extend the computations reported here to lower speeds. (Only one such computation has been made to date, namely for a speed of 36 kt., direction 165°, in connection with a study by Jelesnianski [6] of the surge of July 6, 1954.)

In order to present conveniently the results obtained for the 25 combinations of squall-line propagation speed and direction, the format shown in figure 3 has been selected for use in the subsequent illustrations. The abscissa is propagation speed, and the ordinate is propagation direction.

On all computations the width of the squall line was taken to be 10 n. mi. Although the computing program permits an arbitrary band width, a value smaller than 10 n. mi. probably could not be resolved adequately by the mesh of 2 n. mi. which was used, and a value greater than 10 n. mi. would not be realistic.[3] It should be noted that computations for a given band width cannot be scaled to yield a different effective band width.

In all original computations the pressure rise in the squall line was 4 mb. (0.12 in.) and the wind speed 48 kt. However, since the prediction equations that were used are linear, the predictands can be scaled in direct proportion to the applied pressure gradient and wind stress. In order to make it possible to scale the results independently for pressure gradient and for wind stress, two separate computations were made (for each of the 25 pairs of values of propagation speed and direction), one with pressure rise 4 mb. and wind speed zero, the other with pressure rise 0 mb. and wind speed 48 kt. (Thus, we have at our disposal in reality 50 distinct computations.) In the sequel we refer to the former computation as one with "pressure only," and to the latter as one with "wind only".

The numerical results given later in this paper were obtained by scaling the results of the original computations in the following way—designed for convenience in operational use. The "pressure only" results were scaled to a pressure rise of 0.01 in. through multiplication by 0.08466, the ratio of 0.01 in. to 4 mb. "Wind only" results were scaled to a wind speed of 10 kt. through multiplication by 0.04340, the ratio of $(10\ \text{kt.})^2$ to $(48\ \text{kt.})^2$. Therefore, in the present paper, pressure rise and wind speed in the squall line are

*pressure rise:* 0.01 in.

*wind speed*[4]*:* 10 kt.

This means that surge amplitudes due to "pressure only" can be scaled to an observed pressure rise through multiplication by (observed pressure rise in inches)×100 or, what is the same, by observed pressure rise in hundredths inches; and amplitudes due to "wind only" can be scaled to an observed wind through multiplication by (observed wind speed in knots)$^2$/100.

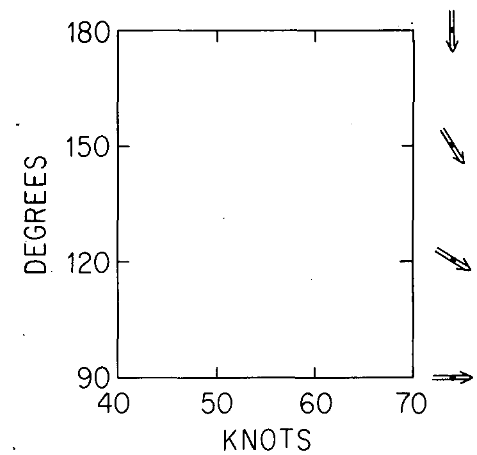


FIGURE 3.—Format for subsequent illustrations. Abscissa: squall-line propagation speed in the range 40 to 70 kt. Ordinate: squall-line propagation direction in the range 90° to 180° clockwise from north (as indicated in fig. 1). Arrows on right show typical propagation directions along ordinate scale.

## 4. AMPLITUDE OF SURGE

The height configuration of the surge of June 26, 1954 (shown at 10-min. intervals in [7]) exemplifies the main events in all cases considered in this paper. As the squall line moves across the Southern Basin toward the southeastern quadrant, it generates an accompanying surge which can be described roughly as a solitary wave of elevation. The developing surge advances into quiescent water and leaves in its wake a broad region of slightly depressed levels. The squall line and surge reach the eastern shore of the Basin at about the same time, after which the surge is reflected while the squall line continues on its southeasterly course and passes off the Lake. The

[3] The band width represents only the zone of pressure rise. The over-all lateral dimensions of the pressure system associated with the squall line may be as much as an order of magnitude greater than the width of this zone.

[4] It should be noted that the wind *stress* (in dynes cm.$^{-2}$) is taken to be $3\times10^{-6}$ (gm. cm.$^{-3}$) times the square of the wind speed (in cm. sec.$^{-1}$). Thus, a wind speed of 10 kt. =515 cm. sec.$^{-1}$ corresponds here to a wind stress of 0.80 dynes cm.$^{-2}$

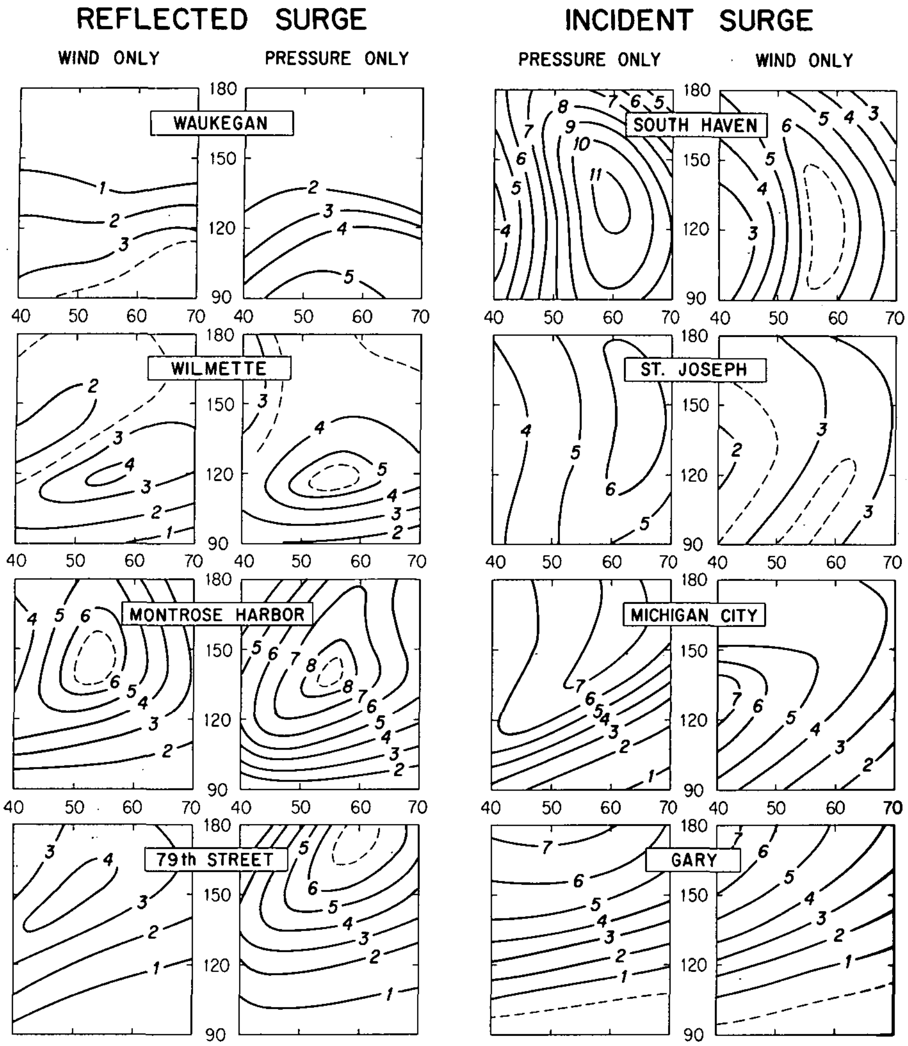


FIGURE 4.—Contours of amplitude of reflected surge at four grid-point stations on western shore of the Basin, and of incident surge at four stations on eastern and southern shores, in the unit 0.01 ft. (See fig. 2 for station locations.) Inner diagrams give "pressure only" results for unit pressure rise of 0.01 in., outer diagrams give "wind only" results for unit wind stress proportional to (10 kt.)[2]. Format is that of figure 3.

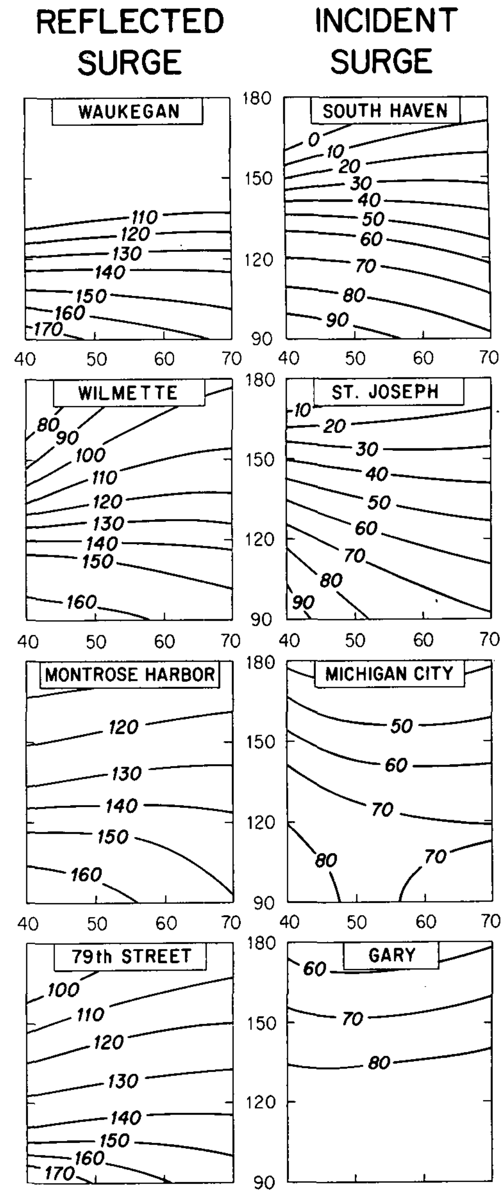


FIGURE 5.—Contours of time interval in minutes between arrival of pressure jump at O'Hare Airport and arrival of surge at grid-point stations. Format is that of figure 3.

reflected surge moves westward and impinges upon the western shore of the Basin as a fully coherent wave.

It is evident from this description that the incident (or "forced") surge will be recorded mainly by stations on the eastern shore, and the reflected (or "free") surge by stations on the western shore. To represent computed characteristics of the incident surge, four grid points were selected at locations adjacent to the shoreline on the eastern and southern sides of the Basin, namely South Haven, St. Joseph, Michigan City, and Gary. Similarly, the reflected surge is represented by four "stations" on the western shore: Waukegan, Wilmette, Montrose Harbor, and 79th Street. (See fig. 2 for locations of these grid-point stations.) Figure 4 shows contours of computed surge amplitude (in unit 0.01 ft.) as a function of squall-line propagation speed (abscissa) and direction (ordinate), for each of the eight selected stations.

To illustrate the use of figure 4, consider the case of a squall line moving with speed 50 kt. and direction 135°. From figure 4 we read that at the Montrose Harbor grid point, the amplitude of the reflected surge will be 0.08 ft. for each 0.01 in. of squall-line pressure rise, and 0.06 ft. for each (10 kt.)[2] of wind stress. Thus, if the actual squall line has a pressure rise of 0.09 in. and winds of

40 kt., the contributions to surge amplitude from pressure and wind are, respectively, 0.08×9=0.72 ft. and 0.06×16=0.96 ft., so the resultant surge amplitude at this grid point is 1.68 ft.

To avoid misinterpretation of figure 4, it should be kept in mind that in the numerical model the distance is 2 n. mi. between grid points at which lake levels are computed. The numerical model therefore is unable to deal explicitly with fine structure of the shoreline, such as small harbors or inlets. For example, the results shown in figure 4 under the name "Montrose Harbor" actually come from a grid point located about 2 n. mi. due east of the entrance to the real Montrose Harbor. Thus, it is apparent that lake levels at a specific point on the actual shoreline are not given directly by figure 4. Such results might be inferred by considering the effects of shoaling at the location in question, or by applying an empirical adjustment factor based upon observations of surge height at shore locations, as has been done by Hughes [4].

The foregoing qualification of the results shown in figure 4 is not intended to apply to the *variation* of surge amplitude with squall-line propagation speed and direction. In other words, the *patterns* of response shown in the figure may be expected to be representative of locations in the neighborhood of each grid point. In this respect, one of the most interesting aspects of the diagrams in figure 4 is the fact that at most stations there is a well-defined point of maximum response. At Montrose Harbor, for example, the maximum surge amplitude is produced by a squall line with speed about 54 kt. and direction about 140°. (This is true for both "pressure only" and "wind only" results.)

The existence of a critical squall-line propagation vector for the Southern Basin of Lake Michigan was first noted by Ewing, Press, and Donn [2], in connection with the surge of June 26, 1954. The squall line in this case moved with speed about 56 kt. and direction 135° during its transit of the Basin. Ewing, Press, and Donn pointed out that a large portion of the region between the 240-ft. and 300-ft. depth contours of the Basin is oriented so as to present a relatively long fetch for surge generation by a squall line moving in the direction of that of June 26, 1954. The significance of these depths is that 240 ft. corresponds to a Lagrangian body-wave speed (gravity × depth)$^{1/2}$ of about 53 kt. and 300 ft. to about 58 kt. Surge generation therefore is promoted by resonant coupling when the squall line moves with a speed in this range.

## 5. ARRIVAL TIME OF SURGE

For each of the eight grid-point stations used in figure 4, figure 5 shows arrival time of the surge, expressed in minutes after the beginning of the squall-line pressure rise at O'Hare Airport (41°59′ N., 87°54′ W.). No distinction is made in figure 5 between "pressure only" and "wind only" results, because arrival times are virtually the same in the two cases.

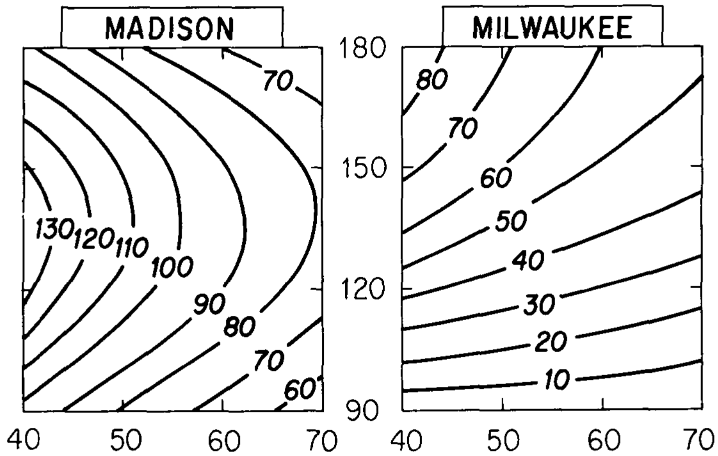


FIGURE 6.—Contours of time interval in minutes for squall-line transit from Madison to O'Hare Airport (left diagram), and from Milwaukee to O'Hare Airport (right diagram). Format is that of figure 3.

From figure 5 we read, for example, that the reflected surge will arrive at Montrose Harbor about 130 min. after pressure-jump arrival at O'Hare Airport, in the case of a squall line moving with speed 50 kt. and direction 135°. The incident surge in this case will reach Michigan City about 65 min. after pressure-jump arrival at O'Hare Airport.

Figure 6 shows squall-line transit time from Madison (43°08′ N., 89°20′ W.) to O'Hare Airport, and from Milwaukee (42°57′ N., 87°54′ W.) to O'Hare Airport. This figure (the result of a simple kinematic computation) can be used to obtain a longer lead time in predicting surge arrival, since for the propagation directions under consideration, the squall line will pass Milwaukee earlier than O'Hare Airport, and Madison earlier than Milwaukee. For example, the pressure jump of a squall line moving with speed 50 kt. and direction 135° will pass Milwaukee 50 minutes before it reaches O'Hare Airport. The arrival time of the incident surge at Michigan City therefore is 65 min. (fig. 5)+50 min. (fig. 6)=115 min. after pressure-jump arrival at Milwaukee.

## 6. ENERGY OF SURGE

Figures 4 and 5 give the main dynamical-numerical results that are likely to be of operational use. A few remarks will be made now on the physical interpretation of these results.

The response curves for Wilmette and Waukegan suggest that on the western shore north of Wilmette, the critical propagation direction is about 90°—which corresponds to a squall line with north-south orientation. On the other hand, at 79th Street and especially at Gary the

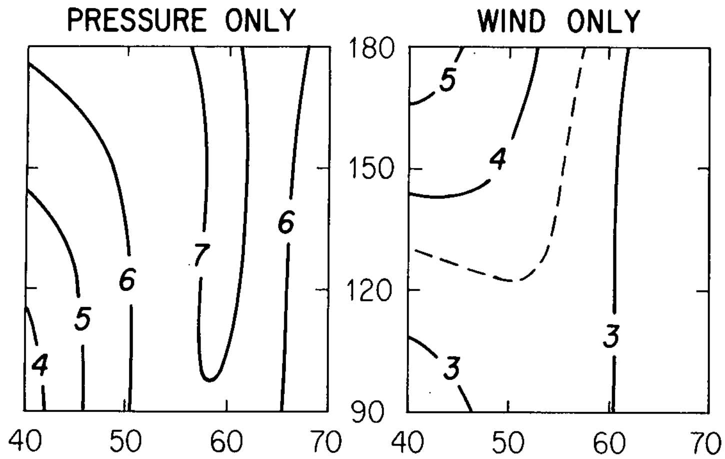


FIGURE 7.—Contours of total energy transmitted to Lake by squall line, in the unit 100 kilowatt-hour=$3.6 \times 10^{15}$ erg. Diagrams on the left give "pressure only" results, for unit pressure rise of 0.01 in.; diagrams on the right give "wind only" results for unit wind stress proportional to (10 kt.)$^2$. Format is that of figure 3.

results suggest that on the southern tip of the Basin, the critical propagation direction is about 180°—which corresponds to a squall line with east-west orientation. Moreover, critical propagation speeds at 79th Street, Gary, and Michigan City are definitely smaller for "wind only" computations than for "pressure only." (At Gary, for example, the critical propagation speed is less than 40 kt.) These results point to the production of edge waves—a mechanism used by Donn and Ewing [1] to account for the surge of July 6, 1954. The squall-line propagation vector in this case was about 35 kt. in magnitude and 165° in direction.

Edge waves have wave fronts perpendicular to the shoreline and maximum amplitude at the shoreline. They move parallel to the shoreline with Stokesian edge-wave speed (gravity $\times$ bottom slope $\times$ wavelength$/2\pi)^{1/2}$ determined by wavelength and by the slope of the lake bottom at the shoreline. For example, from a determination of bottom slopes along the shore of the Southern Basin, we find that for a wavelength of 10 n. mi. the free speed of edge waves varies between about 30 kt. along the relatively steep slopes in the northern part of the Basin, and about 15 kt. along the southern end of the Basin. For a wavelength of 20 n. mi. the corresponding range of wave speeds is about 40 kt. to about 20 kt. In the numerical computations the width of the squall line was 10 n. mi. Therefore, if we assume that the wavelength of edge waves generated by the squall line is about equal to the width of the squall line, it is reasonable to expect resonant generation of edge waves for squall-line speeds in the range 15 to 30 (or at most 40) kt. Moreover, resonance will be promoted when the squall line is perpendicular to the shoreline. The latter condition is met along the western shore when the squall-line propagation direction is in the range 160° to 180°.

Figure 7 illustrates more clearly the difference in overall response of the Lake to pressure gradient and to wind stress. This figure shows contours of total energy transmitted to the Lake by the squall line, as a function of propagation speed (abscissa) and direction (ordinate). The pressure rise produces a well-defined peak in energy transmission for squall-line speeds between 56 and 60 kt. This energy peak—which is virtually independent of propagation *direction* (in the range of directions under consideration)—evidently is the result of resonant coupling with body waves that move with speed (gravity $\times$ depth)$^{1/2}$ in the range 56 to 60 kt., the corresponding depth being about 50 fathoms. No such peak in energy transmission appears when the wind stress acts alone. On the contrary, in this case maximum energy is transmitted for a propagation direction of about 180° (that is, from north to south) and speeds less than 40 kt. This indicates resonance with edge waves that move with speed (gravity $\times$ bottom slope $\times$ wavelength$/2\pi)^{1/2}$, the wavelength being fixed by the width of the squall line.

There are, of course, tendencies for edge-wave resonance in the "pressure only" case, and for body-wave resonance in the "wind only" case. However, the atmospheric pressure-gradient force acting on a vertical water column is proportional to the depth of the column, whereas the wind stress is not dependent upon column depth. This means that edge-wave production (which necessarily is confined to the coastal strip and therefore to shallow water) tends to be subordinate to body-wave production in the "pressure only" case and dominant in the "wind only" case.

## 7. LIMITATIONS OF THIS STUDY

The idealized squall-line configuration in figure 1 bears only the most rudimentary resemblance to the pressure and wind distribution in a real squall line, such as that shown in the paper by Irish [5]. One of the first steps that should be taken beyond the investigation reported here is to make a surge computation in which the atmospheric pressure-gradient force and wind stress are those that correspond to a squall line of record, such as that of August 3, 1960. Such a study doubtless would reveal the limitations of figure 1. It is true that in the absence of a mesometeorological network, it is difficult to obtain squall-line pressure and wind distributions on an operational basis. However, it seems almost certain that operational refinements of figure 1 are possible by means of the existing data network—for example, by use of radar and hourly synoptic data.

With the use of actual pressure data it may be found that a grid interval of 2 n. mi. is not small enough for adequate resolution of the narrow zone of pressure rise on the leading edge of the squall line. Greater resolving power of the grid is important also for another reason. In the present numerical model the shoreline is represented by a zig-zag boundary having the same resolution as that of the basic grid, 2 n. mi. For this reason, with rare exceptions it is not possible to obtain results directly comparable with available observations of water level, since the records at most gages are influenced by fine structure of the shoreline and especially by terminal shoaling of the incoming surge. It follows from these remarks that a significant improvement in the results reported here might be obtained by reduction of the main grid interval for better resolution of the squall line, and by still further reduction in a narrow zone along the shoreline.

The energy diagrams given in the preceding section indicate the existence of a resonant peak associated with edge-wave production for squall lines that move from north to south with speeds in the range 15 to 30 or 40 kt. Since the computations made to date do not cover this range of propagation speeds, it would be desirable to extend them in order to establish more conclusively the role of edge waves.

Finally, it should be noted that among the principal limitations of the dynamical model used in this investigation, the influence of temperature stratification in the Lake, and of bottom friction, should be considered first. Since significant surges occur only in the summer, we are dealing with conditions in which the density distribution in the Lake is better represented by a two-layer model than by a single layer as in the model used here. Friction, since it is a modifying but not a determining factor in the dynamics, probably can be accounted for adequately by relatively simple means.

## ACKNOWLEDGMENTS

For advice and programing assistance I am indebted to J. M. Mihaljan in connection with the surge of June 26, 1954, and to F. Baer in connection with the computations reported in this study. S. M. Irish contributed greatly to the task of analyzing these computations. I also gratefully acknowledge the benefit of collaboration with L. A. Hughes and J. R. Fulks in the Chicago Forecast Center of the U.S. Weather Bureau, and express my thanks to D. L. Harris of the U. S. Weather Bureau, Washington, D.C., for his interest in this work.

## REFERENCES

1. W. L. Donn and M. Ewing, "Stokes' Edge Waves in Lake Michigan," *Science*, vol. 124, No. 3234, Dec. 21, 1956, pp. 1238–1242.
2. M. Ewing, F. Press, and W. L. Donn, "An Explanation of the Lake Michigan Wave of 26 June 1954," *Science*, vol. 120, No. 3122, Oct. 29, 1954, pp. 684–686.
3. D. L. Harris, "The Effect of a Moving Pressure Disturbance on the Water Level in a Lake," *Meteorological Monographs*, vol. 2, No. 10, American Meteorological Society, June 1957, pp. 46–57.
4. L. A. Hughes, "The Prediction of Surges in the Southern Basin of Lake Michigan. Part III. The Operational Basis for Prediction," *Monthly Weather Review*, vol. 93, No. 5, May 1965, pp. 292–296.
5. S. M. Irish, "The Prediction of Surges in the Southern Basin of Lake Michigan. Part II. A Case Study of the Surge of August 3, 1960," *Monthly Weather Review*, vol. 93, No. 5, May 1965, pp. 282–291.
6. C. P. Jelesnianski, *The July 6, 1954 Water Wave on Lake Michigan Generated by a Pressure Jump Passage*, The University of Chicago, Department of Meteorology, M.S. Thesis, Dec. 1958, 47 pp.
7. G. W. Platzman, "A Numerical Computation of the Surge of 26 June 1954 on Lake Michigan," *Geophysica*, vol. 6, No. 3–4, 1958, pp. 407–438.
8. Union Géodesique et Géophysique Internationale, "Bibliography on Generation of Currents and Changes of Surface-level in Oceans, Seas and Lakes by Wind and Atmospheric Pressure, 1726–1955," *Publication Scientifique*, No. 18, Association d'Océanographie Physique, 1957, 83 pp.

[*Received December 21, 1964*]